

# The Benefits of Bimodal Aiding on Extended Dimensions of Speech Perception: Intelligibility, Listening Effort, and Sound Quality

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Elke M. J. Devocht<sup>1</sup>, A. Miranda L. Janssen<sup>1,2</sup>, Josef Chalupper<sup>3</sup>,  
Robert J. Stokroos<sup>1</sup>, and Erwin L. J. George<sup>1</sup>

## Abstract

The benefits of combining a cochlear implant (CI) and a hearing aid (HA) in opposite ears on speech perception were examined in 15 adult unilateral CI recipients who regularly use a contralateral HA. A within-subjects design was carried out to assess speech intelligibility testing, listening effort ratings, and a sound quality questionnaire for the conditions CI alone, CIHA together, and HA alone when applicable. The primary outcome of bimodal benefit, defined as the difference between CIHA and CI, was statistically significant for speech intelligibility in quiet as well as for intelligibility in noise across tested spatial conditions. A reduction in effort on top of intelligibility at the highest tested signal-to-noise ratio was found. Moreover, the bimodal listening situation was rated to sound more voluminous, less tinny, and less unpleasant than CI alone. Listening effort and sound quality emerged as feasible and relevant measures to demonstrate bimodal benefit across a clinically representative range of bimodal users. These extended dimensions of speech perception can shed more light on the array of benefits provided by complementing a CI with a contralateral HA.

## Keywords

cochlear implant, bimodal hearing, speech perception, listening effort, sound quality

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## Introduction

### *Bimodal Aiding*

As inclusion criteria for receiving a cochlear implant (CI) have been expanded to include candidates with hearing loss ranging from severe to moderate, a trend has been observed toward more residual hearing in the nonimplanted ear (Gifford, Dorman, Shallop, & Sydlowski, 2010; Hughes, Neff, Simmons, & Moeller, 2014). More than 60% of a recent sample of unilateral CI recipients with aidable residual hearing opted to retain a conventional hearing aid (HA) in the contralateral ear (Devocht, George, Janssen, & Stokroos, 2015). The bimodal combination of a CI and a HA (CIHA) has the potential of providing access to bilateral, binaural, and complementary cues to overcome some shortcomings in unilateral CI performance (Ching, van Wanrooy, & Dillon, 2007; Olson & Shinn, 2008; Schafer, Amlani, Paiva, Nozari, & Verret, 2011).

In this growing population of bimodal users, it is important to have a set of practicable outcome measures to enable evaluation of the bimodal benefits of speech perception across the full clinical range of aided recipients to optimize hearing performance. The goal for fitting a HA should be to optimize speech understanding while maximizing listening comfort (Hällgren, Larsby, Lyxell, &

<sup>1</sup>Department of ENT/Audiology, School for Mental Health and Neuroscience (MHENS), Maastricht University Medical Center (MUMC+), The Netherlands

<sup>2</sup>Department of Methodology and Statistics, School for Public Health and Primary Care (CAPHRI), Maastricht University (UM), The Netherlands

<sup>3</sup>Advanced Bionics European Research Centre, Hannover, Germany

### Corresponding author:

Elke M. J. Devocht, Department of ENT/Audiology, Maastricht University Medical Center, P. Debyelaan 25, PO 5800, 6202 AZ Maastricht, The Netherlands.

Email: elke.devocht@mumc.nl



Arlinger, 2005) and doing so in a qualitatively acceptable way. This calls for an exploration of the dimensions of intelligibility, listening effort, and sound quality within this context.

### Speech Intelligibility

In the past, clinicians have often not extended testing beyond speech intelligibility in quiet conditions. However, increasingly higher levels of CI performance suggest that testing in quiet does not sufficiently cover the difficulty range to document performance in current CI populations (Ebrahimi-Madiseh, Eikelboom, Jayakody, & Atlas, 2016; Gifford, Shallop, & Peterson, 2008). Beyond the fact that testing in noise better reflects real-life situations than testing in quiet, it has also been shown that speech intelligibility in noise is a better metric for evaluating the maximum potential of bimodal aiding (Dorman et al., 2015). In particular, a set-up with spatially separated speech and noise sources is known to demonstrate the extent to which participants can profit in intelligibility from binaural aiding (Avan, Giraudet, & Büki, 2015).

When testing intelligibility in noise (Schafer et al., 2011), the speech reception threshold (SRT), commonly defined as the signal-to-noise ratio (SNR) at which the listener is able to understand 50% of the signal correctly, can be elicited using an adaptive paradigm (Treutwein, 1995). The advantage of such adaptive procedures is that they are not susceptible to floor or ceiling effects. At the same time, testing in noise with sentences at threshold levels is a difficult task, in particular for CI listeners (Kaandorp, Smits, Merkus, Goverts, & Festen, 2015; Schafer et al., 2011). This can increase uncertainty regarding outcomes, resulting in a higher SRT than the actual SRT (Smits & Festen, 2011) and high test-retest differences (Kaandorp et al., 2015). Kaandorp et al. (2015) recently proposed setting the upper limit for reliable SRT outcomes at +15 dB SNR. Higher levels, namely, suggest that the adaptive procedure has not resulted in a reliable qualification of speech perception according to the speech-intelligibility-index model in stationary noise (ANSI, 1997). More commonly however a selection bias is applied to avoid these difficulties by establishing a minimum required level of performance in quiet (e.g., 50%) before testing in noise (e.g., Buechner, Dyballa, Hehrmann, Fredelake, & Lenarz, 2014; Cullington & Zeng, 2011; Nelson & Jin, 2004). Individual CI scores can range from 0 up to 100% within representative bimodal populations (Devocht et al., 2015; Dorman et al., 2015; Dorman, Gifford, Spahr, & McKarns, 2008; Zhang, Spahr, Dorman, & Saoji, 2013). Information regarding intelligibility testing in noise is then often unreliable or not available for a subgroup of bimodal subjects. The current study

included bimodal subjects across the clinical variety of performance outcomes. Selection criteria for testing intelligibility in noise were not established while documentation was made of subjects who failed to achieve a reliable SRT outcome. Other measures beyond intelligibility were examined to determine their ability to evaluate bimodal speech perception benefits across the total range of bimodal users.

### Extended Dimensions of Speech Perception

Speech perception is multidimensional by nature (Gatehouse & Noble, 2004; Grancharov, Kleijn, Tobergte, & Curtis, 2007; Preminger & Van Tasell, 1995a, 1995b; Sockalingam, Beilin, & Beck, 2009). Commonly distinguished dimensions are as follows: intelligibility or performance, pleasantness or naturalness or satisfaction, loudness, and listening effort or ease. Evaluating HA outcomes should therefore include dimensions beyond aided speech intelligibility, such as sound quality, listening effort, subjective benefit, satisfaction, or use (Humes, 1999). Intelligibility is not only the most commonly tested dimension, but it is also the most dominant one since all other dimensions correlate strongly with the level of intelligibility when intelligibility is allowed to vary over a wide range (Preminger & Van Tasell, 1995b). Other dimensions of speech perception can therefore only be observed as being unique in themselves once the level of intelligibility has been stabilized (Preminger & Van Tasell, 1995a).

*Listening effort.* Listening effort is often loosely defined (Chang, Chang, Lin, & Luo, 2016) but generally refers to the attention and cognitive requirements of speech perception, especially in adverse listening situations (Rönnberg, Rudner, Lunner, & Stenfelt, 2014; Rudner, Lunner, Behrens, Thorén, & Rönnberg, 2012). Listening effort can improve even beyond the level where intelligibility has reached its maximum (Klink, Schulte, & Meis, 2012). Approaches to assess listening effort include subjective, behavioral, or physiological methods (Ohlenforst et al., 2017). It has been suggested that alternative or varying procedures tap into different underlying mechanisms of listening effort (Rudner et al., 2012). A common conceptual framework for listening effort across studies is however lacking (Ohlenforst et al., 2017). When looking for a method that can be easily and quickly applied in a clinical setting (Rudner et al., 2012; van Esch et al., 2013) but at the same time is sensitive to differences between listening conditions (Brons, Houben, & Dreschler, 2013; Hällgren et al., 2005; Humes et al., 1999; Rudner et al., 2012; Zekveld, Kramer, & Festen, 2010), a subjective procedure is often the obvious choice. It is known that binaural listening requires less

listening effort than monaural hearing (Feuerstein, 1992). Reduced effort by bimodal hearing has been observed in the form of shorter response times (Chang et al., 2016; Luo, Chang, Lin, & Chang, 2014). Questionnaire ratings of overall daily effort, however, could not establish a significant difference between subgroups of bimodally aided CI recipients and other groups of CI users (Farinetti et al., 2015; Goman, 2014; Noble, Tyler, Dunn, & Bhullar, 2008). In the current study, a subjective rating procedure was used in an attempt to demonstrate bimodal listening effort benefit as a supplemental dimension of intelligibility.

**Sound quality.** Strictly speaking, sound quality refers to the naturalness of sound, as denoted by its *color*, *timbre*, or *character* (Slawson, 1985). Although a subjective assessment of sound quality is considered valuable and clinically feasible, a generally accepted clinical protocol is lacking (Eisenberg, Dirks, & Gornbein, 1997; Sockalingam et al., 2009). Many studies have assessed sound quality in a one-dimensional way by looking upon it as a preference measurement (e.g. Koning, Madhu, & Wouters, 2015; Suelzle, Parsa, & Falk, 2013) or a broad component in an overall questionnaire (Amann & Anderson, 2014; Gatehouse & Noble, 2004). Nevertheless it has been widely accepted that sound quality is a multidimensional phenomenon (Preminger & Van Tasell, 1995b). When describing characteristics of hearing instruments, multiple perceptual attributes have been used, such as sharpness, clearness, darkness, fullness, nearness, loudness, and smoothness (Balfour & Hawkins, 1992; Boretzki, 1999; Gabriellsson, 1979). It is noted that binaural compared with monaural hearing gives rise to substantial differences in overall impression, fullness, and spaciousness (Balfour & Hawkins, 1992). Hearing electrically by a CI or acoustically by a HA is also known to produce different sound qualities (McDermott & Sucher, 2006). Bimodal listeners report that the CI alone sounds *artificial* and *alien* (Crew, Galvin, Landsberger, & Fu, 2015), while supplementing with the HA bimodally makes sounds more *natural* (Armstrong & Pegg, 1997; Crew et al., 2015; Most, Gaon-Sivan, Shpak, & Luntz, 2012), more *speech-like* (Hamzavi, Pok, Gstoettner, & Baumgartner, 2004), *richer*, and more *colorful* (Zhang et al., 2013). An improvement in sound quality is often a reported reason for CI users to retain a contralateral HA for bimodal listening (Ching et al., 2007; Flynn & Schmidtke, 2004; Scherf & Arnold, 2014; Sucher & McDermott, 2009). The current study aimed to investigate the qualitative benefits of bimodally combining electric and acoustic inputs in opposite ears while considering sound quality in a multidimensional way.

## Current Study

This study aimed at assembling a test battery of speech perception to evaluate the benefits of combining a CI and a HA in opposite ears across a representative group of bimodally aided recipients. Monosyllabic intelligibility scores in quiet were considered as a basic reference. The outcomes and applicability of a spatial speech intelligibility in noise test were evaluated. It was expected that listening bimodally with CI and HA together would improve the SRT within a spatial set-up as compared with listening with CI alone. However, it was anticipated that not all subjects would be able to achieve reliable SRT outcomes when testing intelligibility in noise. It was hypothesized that extended dimensions of speech perception, namely listening effort and multiple attributes of sound quality, would provide extra insights into bimodal aiding and have the benefit of being applicable to a wide range of CI users. By testing at fixed levels of intelligibility, it was expected that listening effort and sound quality could be addressed as being unique dimensions in themselves rather than being related to intelligibility. It was hypothesized that listening bimodally would reduce listening effort as compared with listening with CI alone especially at levels where intelligibility already had reached a maximum. Sound quality ratings were also expected to change when adding the HA aside the CI, particularly for those attributes related to the addition of low-frequency acoustic hearing. The relationship between the observed bimodal benefits and the amount of residual hearing was also examined.

## Materials and Methods

### Ethics

The local Medical Ethical Committee (Maastricht University Medical Center, NL42011.068.13) approved this study as part of a larger clinical trial registered in the Dutch National Trial Register (NTR3932) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation, received a modest participation fee, and were compensated for their traveling expenses.

### Participants

Fifteen bimodal adult patients of the CI team South-East Netherlands were enrolled in this study (eight male and seven female, mean age: 62.0 years, *SD*: 12.5 years). All participants were Dutch speaking, had at least 1 year of regular experience with a CI of the brand Advanced Bionics™ (Valencia, United States) and self-reported

**Table 1.** Subject Characteristics.

Subject	Etiology	CI				HA		
		Ear-side	Experience <sup>a</sup>	Processor	Strategy	Experience <sup>a</sup>	Brand	Type
B03	Meningitis	R	4.4	Harmony <sup>b</sup>	HiRes-S	55	Oticon <sup>c</sup>	Swift I20 +
B06	Otosclerosis	R	5.0	Harmony <sup>b</sup>	HiRes-S/FidI20	26	Siemens <sup>d</sup>	Nitro 701 SP
B08	Unknown	R	7.1	Harmony <sup>b</sup>	HiRes-P/FidI20	51	Oticon <sup>c</sup>	Ino Pro P
B10	Unknown	L	6.0	Naida CI Q70 <sup>b</sup>	HiRes Optima-S	26	Phonak <sup>e</sup>	Naida IX UP
B12	Unknown	R	3.2	Harmony <sup>b</sup>	HiRes-S/FidI20	27	Oticon <sup>c</sup>	Sumo DM
B15	Hereditary; Trauma	R	4.3	Harmony <sup>b</sup>	HiRes-S/FidI20	19	Oticon <sup>c</sup>	Agil
B20	Rubella	L	4.8	Harmony <sup>b</sup>	HiRes-S/FidI20	52	Oticon <sup>c</sup>	Sumo XP
B22	Noise	R	1.8	Harmony <sup>b</sup>	HiRes-P/FidI20	17	Phonak <sup>e</sup>	Naida S I UP
B26	Turner syndrome	R	2.3	Harmony <sup>b</sup>	HiRes-S/FidI20	47	Oticon <sup>c</sup>	380 P
B34	Viral infection	L	3.8	Harmony <sup>b</sup>	HiRes-S	29	Phonak <sup>e</sup>	Naida V UP
B37	Meningitis	R	6.8	Harmony <sup>b</sup>	HiRes-S/FidI20	45	Phonak <sup>e</sup>	Naida S III UP
B42	Cogan syndrome	R	6.5	Harmony <sup>b</sup>	HiRes-S	11	Phonak <sup>e</sup>	Naida V UP
B43	Meningitis	L	4.8	Harmony <sup>b</sup>	HiRes-S/FidI20	61	Phonak <sup>e</sup>	Naida IX UP
B45	Meningitis	R	1.9	Neptune <sup>b</sup>	HiRes-S	42	Phonak <sup>e</sup>	Naida S IX UP
B47	Hereditary; Meniere	R	1.3	Harmony <sup>b</sup>	HiRes-S/FidI20	28	Phonak <sup>e</sup>	Naida V UP

CI = cochlear implant; HA = hearing aid; R = right; L = left.

<sup>a</sup>Expressed in years.

<sup>b</sup>Advanced Bionics<sup>TM</sup> (Valencia, United States).

<sup>c</sup>TM(SmØrum, Denmark).

<sup>d</sup>TM(Erlangen, Germany).

<sup>e</sup>TM(Stäfa, Switzerland).

that they consistently used a conventional HA in the contralateral ear for at least 50% of the day. Details on the participants' individual hearing situation are presented in Table 1. Unaided and aided hearing thresholds in the HA-ear are plotted in Figure 1. Participants were found to have considerable residual hearing in the HA-ear with acoustically audible thresholds of up to 1000 Hz on average. The mean pure-tone average (PTA across 250, 500, and 1000 Hz) was found to be 81.6 dB HL (*SD*: 18.3 dB) in the unaided and 36.0 dB HL (*SD*: 7.4 dB) in the aided situation.

## Procedures

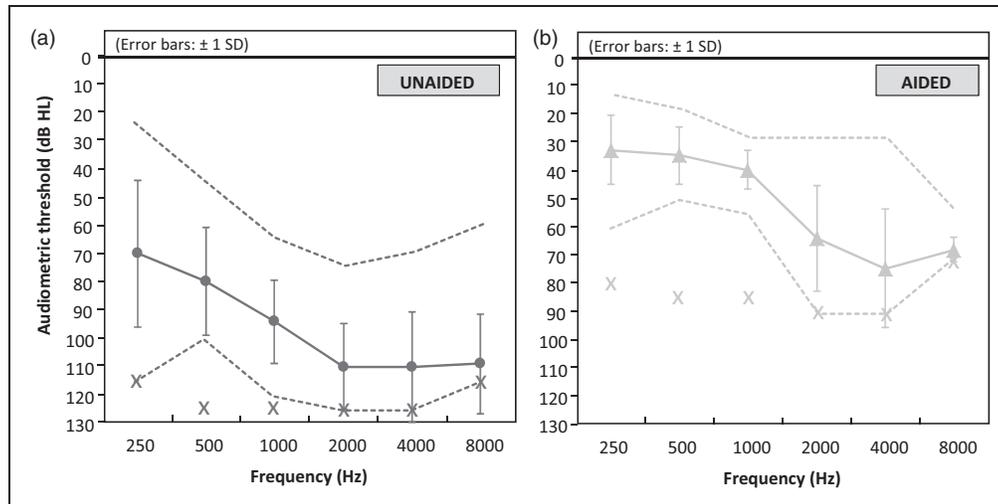
A within-subjects design was used to assess the performance of bimodal CI recipients on different dimensions of speech perception: speech intelligibility, listening effort, and sound quality.

Measurements were performed in a sound-attenuated booth during one acute test session. The order of tests was fixed across participants. The spatial speech-in-noise test was performed first. Then the sound quality scales were completed, followed by listening effort rating. To counteract fatigue, breaks were taken between and during tests when necessary.

All participants used their own hearing devices at typical daily use settings and manipulations during the

course of testing were not allowed. Both the CI speech processor and the HA were checked to ensure they were working correctly. There were two participants whose CI speech processor was different from the others (see Table 1). For these participants, the daily CI mapping was adopted into a Harmony<sup>TM</sup> speech processor with T-mic<sup>TM</sup> (Frohne-Büchner, Büchner, Gärtner, Battmer, & Lenarz, 2004) to achieve consistency across participants. When testing a monaural condition, the contralateral device was turned off and left in situ. Since the CI-ear is assumed to be the primary speech input for most of the CI-recipients (Neuman et al., 2017), the primary outcome of bimodal benefit was defined as the benefit of listening with CI and HA together compared with the reference of listening with CI alone. As a consequence and by taking test and time constraints into account, the outcomes of the spatial speech-in-noise test and listening effort rating were not measured for the HA alone condition.

*Speech intelligibility in quiet.* Word intelligibility was retrieved from the last standard clinical routine measurement (less than 12 months prior to the acute test session). The maximum phoneme score (%) over the levels 55, 65, and 75 dB SPL on a Dutch monosyllabic consonant-nucleus-consonant (CNC) intelligibility test (Bosman & Smoorenburg, 1995) was recorded in quiet from the



**Figure 1.** Residual hearing. Mean pure-tone air conduction thresholds in the hearing aid ear for the unaided situation under headphones (a) and the aided situation in free field (b). Dashed lines denote the range of observed thresholds. If no response could be recorded within the limits of the audiometer, a value of 5 dB HL greater than the maximum tested level was entered (see X markings).

frontal direction for the listening condition with CI, with HA, and with CIHA together.

*Spatial speech intelligibility in noise.* Sentence intelligibility in noise was tested with the optimized version of the Dutch Matrix test (Houben & Dreschler, 2015) within a set-up of spatially separated speakers. The Dutch Matrix material is based on a closed speech corpus of sentences with an identical syntactical structure: “name, verb, numeral, adjective, object,” for example, “Mark gives five large flowers.” The accompanying Dutch Matrix noise is a stationary noise with an average power spectrum equivalent to that of the sentences. More information on the development of the Dutch Matrix material is available in Houben et al. (2014) and Houben & Dreschler (2015). This corpus of sentences has low linguistic complexity without redundancy, making it well suited for repetitive testing (Houben et al., 2014). This speech material has been shown to be applicable for use in CI recipients (Theelen-van den Hoek, Houben, & Dreschler, 2014).

The test was calibrated and administered using the Oldenburg measurement applications software package developed by HörTech gGmbH, Oldenburg, Germany ([www.hoertech.de](http://www.hoertech.de)). Participants were asked to reconstruct the sentence by selecting the perceived words from 10 alternative tokens within each of the five word categories (“name, verb, numeral, adjective, object”). The participant gave their responses by using a touch screen with a visual representation of the closed-set speech corpus. To force an answer, the use of an “I don’t know”-button was not allowed.

Speech was presented from a speaker at ear level at a distance of 1 m in the front (0°) while the stationary Dutch Matrix noise was played continuously from the

same speaker (S0N0), a speaker at 90° on the HA-side (S0Nha), or a speaker at 90° on the CI-side (S0Nci). This set-up is known to be able to demonstrate the benefits of binaural aiding for speech perception in noise (Avan et al., 2015).

The noise was maintained at a fixed level of 65 dB SPL while the first sentence started off at a level of +5 dB SNR. Each sentence was scored as percentage of words correct. With each subsequent sentence, the speech level was adjusted according to an adaptive procedure that uses a logistic function (Brand & Kollmeier, 2002) to converge at the SNR corresponding to a 50% correct score, defined as the SRT.

Each list consisted of 20 sentences with an average test time of 5 minutes. The sequence of lists was kept constant for all participants to avoid the situation where a participant could be presented with the same list twice. To address potential learning effects (Theelen-van den Hoek et al., 2014) and familiarize participants with the task, one training list for the spatial condition S0N0 was administered prior to starting the actual test in the first listening mode (CI or CIHA). The result of this training list was excluded from the analysis.

Subsequently each of the three spatial conditions (S0N0, S0Nha, S0Nci) was tested and retested for the listening condition with CI alone and with CIHA together, resulting in a total of 12 lists per participant. The listening condition (CI, CIHA) to start with was randomized between participants and completed before shifting to the other listening condition in order to avoid frequent swapping of hearing devices. The order of testing the three spatial conditions was randomized across participants but kept constant within each participant across listening conditions and between test and retest.

In the occasional case where the adaptive procedure evoked an invalid SRT outcome, defined as a SNR result outside the range of presented levels or above 15 dB SNR (Kaandorp et al., 2015), the result of the affected test condition was omitted from analysis. If there were two valid outcomes, the final result per condition was calculated as the mean of test and retest.

**Listening effort in noise.** The set of unique sentences from the Dutch Matrix speech corpus (Houben & Dreschler, 2015) was also used to evaluate listening effort in noise. The listening effort test is based on subjective ratings for the ease or difficulty involved in listening to speech in the presence of varying amounts of noise. This test has been developed within the framework of the European HearCom (Hearing in the Communication Society) project ([www.hearcom.eu](http://www.hearcom.eu)) to evaluate individual listening effort in a specific communication situation or with a distinct HA algorithm. The procedure has been validated as a scaling procedure at different SNRs using stationary and fluctuating background noise (Schulte, Wagener, Vormann, Dillier, & Büchner, 2008) and has since been applied in several other studies (Brons, Houben, & Dreschler, 2012; Harlander, Rosenkranz, & Hohmann, 2012; Luts et al., 2010; van Esch et al., 2013). The test was administered using the Oldenburg measurement applications software package developed by HörTech gGmbH, Oldenburg, Germany ([www.hoerotech.de](http://www.hoerotech.de)). Rating was performed using a vertical scale with 13 discrete points (seven named categories interspersed with an empty category) ranging from *no effort* (Score 0) to *extreme effort* (Score 12; Luts et al., 2010). One randomly selected sentence from the Dutch Matrix corpus was repeated until the participant could confidently provide a self-rating of the listening effort using a vertical scale displayed on a touch screen. Listening effort was assessed for the listening condition with CI alone and with CIHA together. The listening condition to start with was randomized between participants.

The Dutch Matrix speech and stationary noise were emitted concurrently at a distance of 1 m in the front (0°; S0N0) from a speaker at ear level. The noise level was fixed at 65 dB SPL, while the speech level was set according to the participant's individual SRT resulting from the spatial speech-in-noise test in the corresponding listening condition for the spatial condition S0N0. This means that when testing at SRT level, intelligibility was by definition fixed at the 50%-point for all participants in all modes, making it possible to evaluate listening effort on top of intelligibility. When a SRT outcome could not be determined below 15 dB SNR (Kaandorp et al., 2015), a value of 15 dB was assigned. Overall, six levels were set between 6 dB below and 9 dB above the participant's individual SRT in steps of 3 dB (SRT-6, SRT-3, SRT,

SRT + 3, SRT + 6, SRT + 9). Following one practice run in the first listening mode, each level was presented five times, resulting in a total of five sentence ratings per level. A random presentation order was applied, which differed between listening conditions and across participants. The final result per level was calculated as the mean of these five ratings.

**Sound quality.** The quality of bimodal speech perception was evaluated with a multidimensional questionnaire. The questionnaire was based on the inventory of quantifiable sound quality attributes as described by Boretzki (1999) within the field of hearing instrument fitting. The initial set of 21 descriptors was translated into Dutch and back-translated to the original German as well as the published English wording by two Dutch native speakers with Master degrees in German and English. Based on the Dutch translation, a pilot survey was carried out among a group of 18 bimodal listeners (unpublished data), who were asked to indicate those features that are most relevant to describe their hearing situation with CI, HA, and CIHA together. The 10 most frequently selected features were identified. Each of these 10 features was extracted by 35% or more of the bimodal patients and was not identified as being too difficult in terms of phrasing. The 10 most selected sound quality features (Table 2) were then used to comprise the resulting bimodal questionnaire. In his original study, Boretzki (1999) suggested a relationship between the sound quality features and the frequency region in which they are expected to be sensitive for particular acoustical modifications as a starting point for improving HA fittings. Since residual hearing in the nonimplanted ear is known to be situated mainly in the low-frequency acoustic region, one could expect the effect of bimodal hearing to appear as intensifications of the attributes *full* and *dull* while attenuating attributes that are associated with high-frequency information (Table 2).

The questionnaire used in this study asked participants to describe "how a familiar speaker in quiet conditions sounds" to them by rating the set of 10 sound quality attributes on a linear ruler from 0 (*not at all*) to 10 (*very*) to a precision of 0.1. Ratings were assessed for the situations with CI, with HA, and with CIHA together in this fixed order. The sound quality attributes were presented in a random order (Table 2) that was kept constant across participants. Participants were also asked to rate the overall difficulty of the questionnaire using the same ruler.

### Data Analysis

All statistical analyses were performed using IBM SPSS Statistics version 23.0.0.2. In case of missing data points,

**Table 2.** Bimodal Questionnaire of Sound Quality Features.

English <sup>a</sup>	Dutch	Acoustical sensitivity <sup>a</sup>	Test order
Voluminous or full	Vol of volumineus	Low frequencies	1
Dull or damped	Dof	Low frequencies	6
Sharp	Scherp	High frequencies	4
Bright or harsh	Helder of Fel	High frequencies	5
Tinny or metallic	Blikkerig of Metaalachtig	High frequencies	10
Shrill	Schel	Narrow band high frequency emphasis	3
Hard	Hard	More likely high frequencies	2
Nasal	Nasaal	More likely high frequencies	9
Unclear or blurry	Vaag of Wazig	Unspecific	8
Unpleasant	Onaangenaam	Unspecific	7

<sup>a</sup>Based on the inventory of quantifiable sound quality features (Boretzki, 1999).

the cause was ascertained. When structural nonresponse was observed, referring to multiple untestable conditions within one participant, these cases were described and excluded from the analysis of the affected outcome measure. When data points were established to be missing at random, the mean of 100 imputations was used to replace missing values (Graham, Olchowski, & Gilreath, 2007). Normality was checked with the Shapiro–Wilk test and visual inspection of the outcome distributions. Overall mean pairwise differences are presented accompanied by the standard error, except where median differences were considered given the nonnormal distribution of scores. Bonferroni adjustments for multiple comparisons were applied with  $p < .05$  indicating statistical significance.

Pairwise comparisons were performed for the dimensions of speech intelligibility in quiet and sound quality for the three listening conditions (CI-HA-CIHA). Parametric two-tailed paired-samples student  $t$  tests were conducted for speech intelligibility in quiet. Since sound quality ratings did not appear to be normally distributed, the nonparametric two-tailed Wilcoxon signed rank test was applied to each of the 10 sound quality attributes.

When using percentage speech intelligibility scores, the room for bimodal improvement is known to be restricted if the score with CI alone is already high (Dorman et al., 2015). Therefore, the “normalized bimodal benefit” was also calculated for speech intelligibility in quiet by dividing the measured change by the potential change, in case of an improvement (CIHA-CI/100-CI) as well as a drop in performance (CIHA-CI/CI), and multiplying this quotient by 100 to produce an indexed score with a possible range of  $-100$  to  $100$  percentage points (Zhang et al., 2013). A one-sample  $t$  test assessed whether the normalized bimodal benefit differed significantly from zero.

The dimensions of spatial speech intelligibility in noise and listening effort were both determined using multiple measures within each test condition. To evaluate test–retest reliability, intraclass correlation coefficients (ICCs) were obtained for the two repeated measures of speech intelligibility in noise and the five repeated measures of listening effort. A one-way random ICC model (Shrout & Fleiss, 1979) was selected since variability across participants and across repeated measurements could not be disentangled statistically. This result stemmed from the fact that different participants were assessed using different sentence lists (speech intelligibility in noise) or using different sentences (listening effort) from the Dutch Matrix speech material.

For both the dimensions of spatial speech intelligibility in noise and listening effort, two factors were assessed. These two factors were listening condition (CI-CIHA) and spatial condition (S0N0, S0Nci, S0Nha) for speech intelligibility in noise. For listening effort, the two conditions were listening condition (CI-CIHA) and test level (SRT-6, SRT-3, SRT, SRT+3, SRT+6, SRT+9). Therefore a two-way repeated-measures analysis of variance (ANOVA) was performed. Where the ANOVAs revealed statistically significant differences after applying a Greenhouse-Geisser adjustment to correct against violations of sphericity, post hoc comparisons between different levels of the factors were made with the two-tailed paired-samples student  $t$  tests.

Given the small sample size, an explorative correlation analysis using Spearman correlations without any predefined corrections was performed as a first attempt to explore the relations between the different dimensions of observed bimodal benefits. The correlation between bimodal benefits and the unaided and aided residual hearing (PTA) in the HA ear was also calculated.

## Results

Raw scores across the dimensions of speech in quiet, spatial speech in noise, listening effort, and sound quality are presented in Supplementary Appendices A and B. The ICC is also given for those dimensions having an outcome based on multiple measures within a test condition.

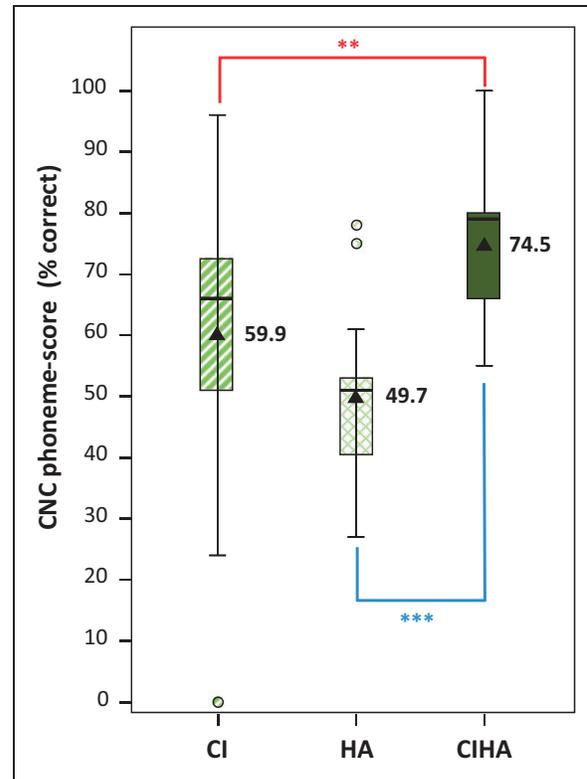
### Speech Intelligibility in Quiet

Mean CNC phoneme-scores for the CI, HA, and bimodal listening conditions are presented in Figure 2. The average score with CI was  $10.3 \pm 7.1$  percentage points higher than with HA, but this difference was not statistically significant ( $p = .516$ ). The difference between CI and HA was less than 10 percentage points for four participants. The CI outperformed the HA by 10 percentage points or more for eight participants. For three participants, the HA provided better monaural performance by at least 10 percentage points. The primary outcome of bimodal benefit, defined by comparing the bimodal combination CIHA to the CI alone, was found to be statistically significant with a mean improvement of  $14.6 \pm 4.1$  percentage points ( $p = .009$ ). For all the participants except two, some bimodal improvement in percentage points was observed. Listening with CIHA compared with the HA alone showed a significant improvement of  $24.9 \pm 3.6$  percentage points ( $p < .001$ ). The normalized bimodal benefit was found to be significantly different from zero by  $36.2 \pm 7.0$  percentage points ( $p < .001$ ).

### Spatial Speech Intelligibility in Noise

Where test and retest outcomes were available, the ICC for the spatial speech-in-noise test was found to be 0.7 or higher over all conditions. According to the classification scale of Landis and Koch (1977), an ICC for a single assessment greater than 0.6 is substantial and greater than 0.8 is almost perfect.

For the individual SRT outcomes in noise, one participant was unable to perform in all conditions while three participants could not perform in the CI alone conditions. These cases (B03, B12, B43, and B45) were therefore excluded from further analysis. Another participant (B15) featured one specific condition missing at random for which a value was imputed. Five of the remaining participants had just one outcome in one or two of the tested conditions due to the applied outcome restrictions. Given the fact that ICC values indicated a substantial reliability for the single assessment, the single assessment was taken for those specific conditions rather than the average of two assessments, as occurred in all other conditions and other participants.

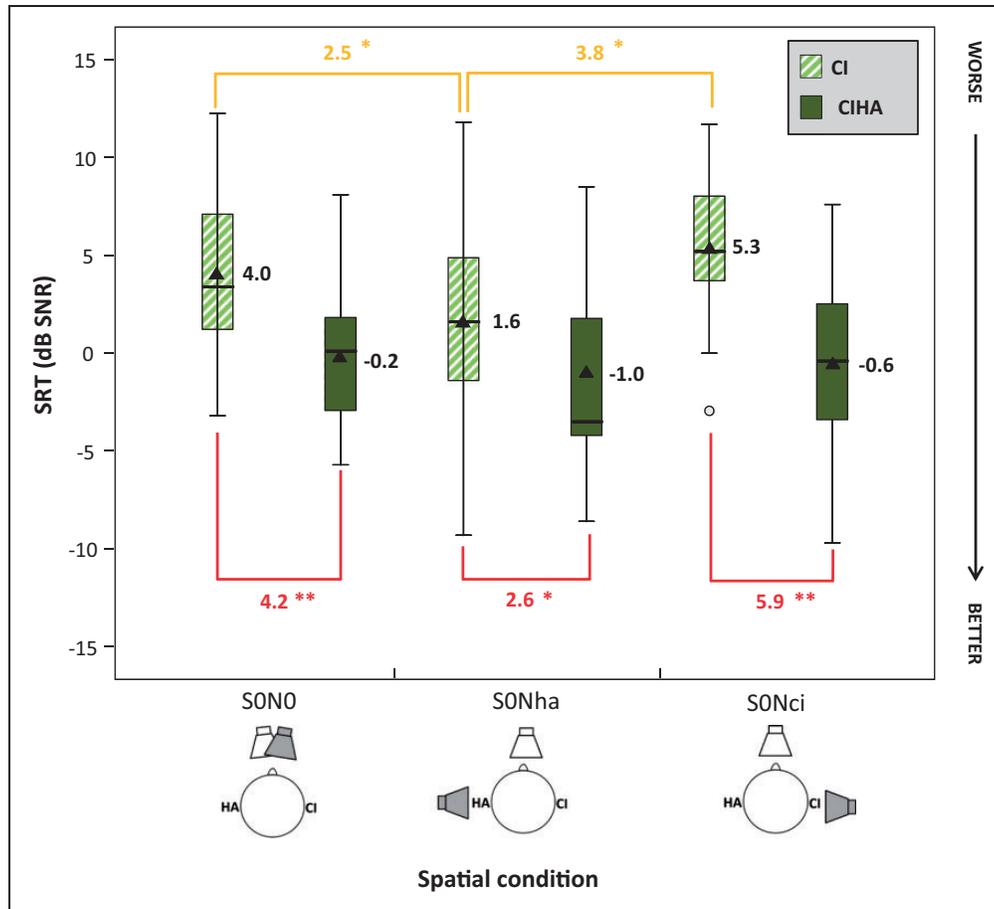


**Figure 2.** Speech in quiet. CNC phoneme-scores (% correct) in quiet for the listening condition with CI, HA, and CIHA. Box plots represent the distribution per condition (median and interquartile range), with whiskers denoting minimum and maximum values within 1.5 times the interquartile range and circles denoting outliers. Triangles highlight the annotated mean value per condition. Asterisks denote significant differences between listening conditions (\*\* $p < .01$ . \*\*\* $p < .001$ ).

CI = cochlear implant; HA = hearing aid; CIHA = CI and HA in contralateral ears (bimodal hearing); CNC = consonant-nucleus-consonant.

The average SRT outcomes between listening conditions (CI, CIHA) and across spatial settings (S0N0, S0Nha, S0Nci) are shown in Figure 3. At an individual level, all participants demonstrated a bimodal SNR improvement in all spatial conditions, except for two participants who showed a comparable outcome in the S0Nha setting. The ANOVA revealed a significant main effect of the factor *listening condition*  $F(1.0, 10.0) = 31.7$ ,  $p < .001$ ,  $\eta_p^2 = 0.76$ . The main effect of *spatial condition* was not found to be significant,  $F(1.3, 12.8) = 2.9$ ,  $p = .107$ ,  $\eta_p^2 = 0.22$ . However, since the interaction effect between the factors *listening condition* and *spatial condition* was statistically significant,  $F(1.7, 17.0) = 6.5$ ,  $p = .010$ ,  $\eta_p^2 = 0.40$ , the effects of these two factors were investigated separately.

When comparing the SRT outcome between the bimodal (CIHA) and the unilateral (CI) listening



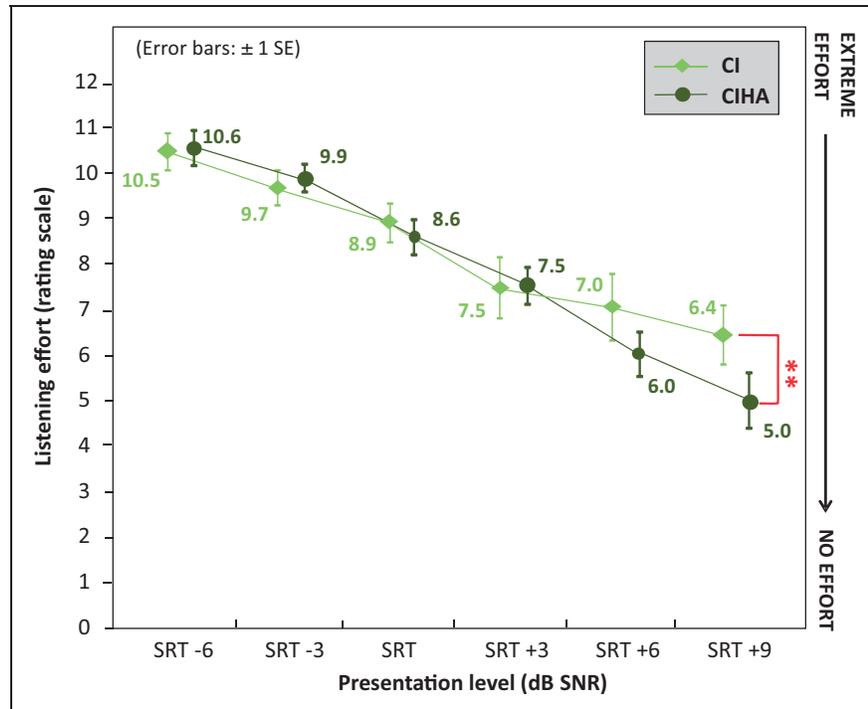
**Figure 3.** Spatial speech in noise. Results for the spatial conditions with speech and noise from the front (SON0), speech from the front while noise from the HA side (SONha), and speech from the front while noise from the CI side (SONci). Each spatial condition was assessed for the listening condition with CI and CIHA. Box plots represent the distribution per condition (median and interquartile range), with whiskers denoting minimum and maximum values within 1.5 times the interquartile range and circles denoting outliers. Triangles highlight the annotated mean value per condition. Monaural effects are indicated in yellow (top) and bimodal effects in red (bottom). Asterisks denote significant differences between listening conditions (\* $p < .05$ , \*\* $p < .01$ ). SRT = speech-reception threshold; CI = cochlear implant; CIHA = CI and HA in contralateral ears (bimodal hearing); SNR = signal-to-noise ratio.

conditions, the benefit of bimodal aiding can be determined for each spatial condition. With speech and noise coming from the front (SON0), adding the HA provided a mean significant benefit of  $4.2 \pm 0.9$  dB SNR ( $p = .002$ ). For the setting with noise coming from the HA-side (SONha), a significant improvement of  $2.6 \pm 0.7$  dB SNR ( $p = .014$ ) was observed when the HA was added. In the condition with noise originating from the CI-side (SONci), a significant gain of  $5.9 \pm 1.1$  dB SNR ( $p = .001$ ) occurred by adding the HA. Monaural effects can be addressed by comparing the different spatial settings for the listening condition with CI alone. A significant improvement of  $2.5 \pm 0.6$  dB SNR ( $p = .011$ ) and  $3.8 \pm 1.0$  dB SNR ( $p = .020$ ) was seen when the noise was shifted an angle of  $90^\circ$  (SON0 to SONha) or  $180^\circ$  (SONci to SONha), respectively, in the shadow of the head to the contralateral side.

When comparing spatial settings for the bimodal listening condition, one can evaluate spatial release from masking, which is defined as the benefit of spatially separating the speech and noise source. The data did not show a significant effect ( $p > .05$ ), either for the HA-side (SON0 to SONha,  $0.8 \pm 1.0$  dB SNR) or the CI-side (SON0 to SONci,  $0.4 \pm 1.0$  dB SNR). Even though it is expected that the best performing ear side will vary per subject, it is not possible to evaluate spatial release from masking toward the best performing monaural side since HA-alone performance for speech recognition in noise was not assessed here.

### Listening Effort in Noise

The reliability (ICCs) of listening effort ratings for each level in each listening condition based on a single



**Figure 4.** Listening effort in noise. Mean listening effort ratings on a scale of 0 (*no effort*) to 12 (*extreme effort*) for speech and noise presented from the front (S0N0) when listening with CI and CIHA. Listening conditions are slightly offset on the x axis to improve readability. Tested levels of SRT-6, SRT-3, SRT, SRT + 3, SRT + 6, and SRT + 9 are expressed as relative to the participant's individual SRT on the spatial speech in noise task in the corresponding condition. Asterisks denote significant differences between listening conditions (\*\* $p < .01$ ).

SRT = speech-reception thresholds; CI = cochlear implant; CIHA = CI and HA in contralateral ears (bimodal hearing); SNR = signal-to-noise ratio.

assessment ranged from fair ( $>0.2$ ) to substantial ( $>0.6$ ), whereas the average of five assessments was found to be substantial ( $>0.6$ ) to almost perfect ( $>0.8$ ; Landis & Koch, 1977). All participants successfully completed all rating conditions. The mean ratings across levels (SRT-6, SRT-3, SRT, SRT + 3, SRT + 6, SRT + 9) and between listening conditions (CI, CIHA) are displayed in Figure 4. The ANOVA revealed no significant main effect of the factor *listening condition*  $F(1.0, 14.0) = 1.7$ ,  $p = .215$ ,  $\eta_p^2 = 0.11$ . The main effect of the factor *test level* was statistically significant,  $F(1.3, 18.2) = 38.3$ ,  $p < .001$ ,  $\eta_p^2 = 0.73$ , as was the interaction term between the factors *listening condition* and *test level*  $F(3.6, 50.0) = 5.3$ ,  $p = .002$ ,  $\eta_p^2 = 0.27$ . The effects of these two factors were therefore analyzed separately.

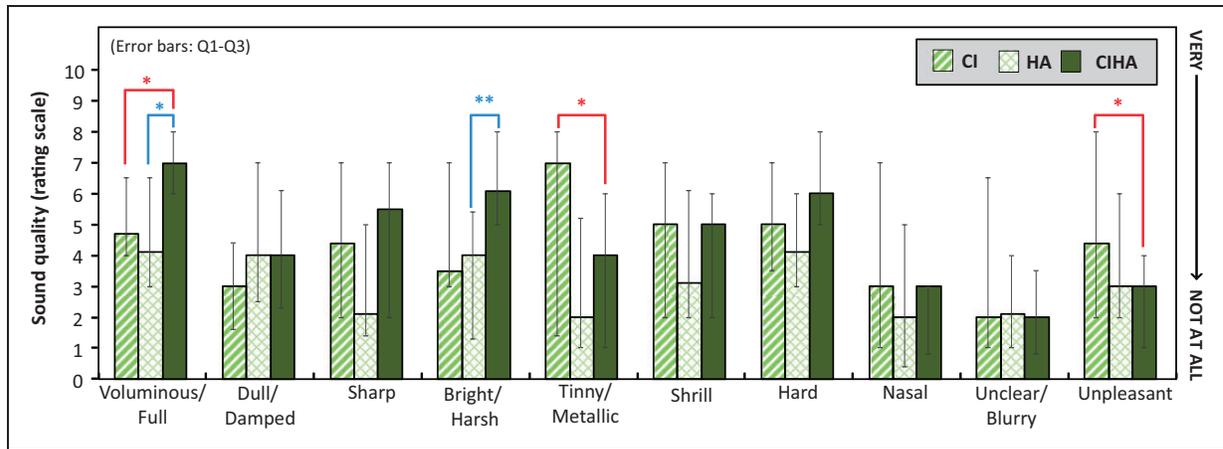
The investigation into bimodal benefit by comparing CIHA to CI revealed no significant effect over the levels SRT-6 up to SRT + 3. At the level of SRT + 6, a decline of  $1.0 \pm 0.4$  points lost statistical significance after Bonferroni correction ( $p = .18$ ). At the most favorable tested level of SRT + 9, all participants except one reported a reduction in listening effort of up to 4.4 points with an average reduction of  $1.4 \pm 0.3$  points ( $p = .007$ ).

Two one-way ANOVAs demonstrated the effect of level to be highly significant ( $p < .001$ ) whereby the rated effort decreased linearly with increasing level when listening with CI,  $F(1, 14) = 28.3$ ,  $p < .001$ ,  $\eta_p^2 = 0.7$ , as well as bimodally,  $F(1, 14) = 58.7$ ,  $p < .001$ ,  $\eta_p^2 = 0.8$ . For each 3 dB step toward a more favorable SNR level, an average of 0.8 and 1.1 points reduction in listening effort was seen for CI and CIHA, respectively.

### Sound Quality

A median questionnaire score of 6.0 out of 10 was obtained for overall difficulty. No missing data occurred since all participants were able to provide a rating for all 10 sound quality attributes.

Median ratings for the listening conditions (CI, HA, CIHA) across the 10 sound quality attributes are shown in Figure 5. None of the questioned attributes showed a significant difference in perceived sound quality between CI and HA. The bimodal condition however was rated to be significantly more voluminous (2.9 points,  $p = .022$ ) and brighter (2.1 points,  $p = .006$ ) when compared with the HA condition, while being perceived more



**Figure 5.** Sound quality. Median ratings of 10 sound quality features on a scale of 0 (*not at all*) to 10 (*very*) when listening to a familiar speaker with CI, HA, and CIHA. Asterisks denote significant differences between listening conditions ( $*p < .05$ .  $**p < .01$ ). CI = cochlear implant; CIHA = CI and HA in contralateral ears (bimodal hearing); HA = hearing aid.

voluminous (2.3 points,  $p = .017$ ), less unpleasant (1.4 points,  $p = .032$ ), and less tinny (3.0 points,  $p = .013$ ) when compared with the CI alone condition.

### Exploratory Correlation Analysis

The correlations between bimodal benefits on the different dimensions of speech perception are presented in Table 3. The bimodal benefit for the spatial condition S0Nci was found to correlate with the bimodal effect for the spatial condition S0N0 as well as with the normalized bimodal benefit of intelligibility in quiet. The bimodal benefit for the spatial condition S0N0 also correlated positively with the build-up of the sound quality descriptor *voluminous or full*. No correlations were found between the reduction of listening effort at SRT +9 and any other measure of bimodal benefit.

The unaided PTA in the HA ear was found to correlate with the degree of bimodal benefit in the condition S0Nha and the reduction in the sound quality feature *tinny or metallic*. The PTA aided with HA was related to all demonstrated bimodal benefits of sound quality: an increase of *voluminous or full*, a decrease of *unpleasant*, and a reduction of *tinny or metallic*. These correlations indicate that lower and therefore more favorable hearing thresholds are related to more change in sound quality.

## Discussion

### Speech Intelligibility in Quiet

Speech intelligibility in quiet remains the most widely used outcome measure in CI rehabilitation practice aside from audibility (Vaerenberg et al., 2014). In the current study, most participants (12 out of 15) scored

better or about equal with CI when compared with HA alone. This finding supports the used definition of bimodal benefit as the monaural condition with CI alone supplemented with HA. It should however be noted that outcome differences between CI and HA were not found to be significant. This most likely reflects the fact that our sample included persons with a substantial degree of aidable residual hearing on the HA-side up to 1000 Hz. Compared with other studies (e.g., Gifford, Dorman, Sheffield, Teece, & Olund, 2014; Neuman et al., 2017), the average speech intelligibility score observed with the HA is rather high (49.5%). The current sample is believed to be representative of the current bimodal population, as more and more patients with considerable residual hearing are being implanted. A recent bimodal population study by the same authors (Devocht et al., 2015) reported an average CNC score of 41% when aided with a HA.

Overall a significant bimodal benefit of 15 percentage points was observed, suggesting a large summation effect in quiet. Bimodal improvements on monosyllabic word scores in quiet between 10 and 20 percentage points have also been reported in other studies (Devocht et al., 2015; Dorman et al., 2008; Gifford, Dorman, McKarns, & Spahr, 2007; Gifford et al., 2010; Iwaki et al., 2004; Park, Teagle, Buss, Roush, & Buchman, 2012; Sheffield & Gifford, 2014; Zhang, Dorman, & Spahr, 2010; Zhang et al., 2013). Dorman et al. (2008) noted that the lowest scores in the CIHA condition were near the mean score for the CI alone condition, as was also found here (Figure 2). Although none of the individual participants in the current population displayed reduced performance in the bimodal as compared with the CI alone listening situation, not all of them obtained a benefit. While it is considered an important basic characteristic of monaural

**Table 3.** Correlation Matrix of the Bimodal Benefits on Speech Perception.

Bimodal benefits speech perception	Bimodal benefits on speech perception										Residual hearing			
	Spatial intelligibility in noise					Listening effort					Speech quality		PTA <sup>b</sup>	
	S0N0	S0Nha	S0Nci	SRT + 9	Voluminous or Full	Tinny or Metallic	Unpleasant	Unaided	Aided					
Normalized CNC	0.47	0.48	0.71*	0.25	0.10	0.26	0.08	0.34	0.14					
	$\rho^a$													
S0N0	.142	.133	.015	.371	.736	.352	.775	.209	.614					
	$\rho^a$													
S0Nha	–	.259	.010	.796	.021	.202	.206	.242	.159					
	$\rho^a$													
S0Nci	–	–	.160	.279	.171	.237	.904	.003	.075					
	$\rho^a$													
SRT + 9	–	–	–	.518	.066	.275	.656	.293	.229					
	$\rho^a$													
Voluminous or full	–	–	–	1.00	0.15	0.24	0.01	0.11	0.04					
	Sig													
Tinny or metallic	–	–	–	–	.590	.387	.985	.695	.898					
	$\rho^a$													
Unpleasant	–	–	–	–	1.00	0.04	0.30	0.32	0.53*					
	$\rho^a$													
	Significance				–	.898	.276	.241	.042					
	$\rho^a$													
	Significance					1.00	0.46	0.54*	0.62*					
	$\rho^a$					–	.086	.039	.013					
	Significance													
	$\rho^a$						1.00	0.17	0.60*					
	Significance													
								.542	.017					

<sup>a</sup>Absolute spearman rho correlation coefficients are presented, the direction of significant correlations is described in the text of the manuscript.

<sup>b</sup>Pure-tone average across 250, 500 and 1000 Hz at the hearing aid side.

\* $p < .05$ . \*\* $p < .01$ .

hearing, speech perception in quiet might not be the optimal measure to assess bimodal benefit (Dorman et al., 2015; Neuman et al., 2017). Not only is speech intelligibility in quiet susceptible to ceiling effects, it might not be the most relevant measure to evaluate everyday speech perception.

### *Spatial Speech Intelligibility in Noise*

Speech intelligibility in noise is often suggested as being more relevant than testing speech intelligibility in quiet (e.g., Gifford et al., 2008). When testing in a spatial set-up, bilateral and binaural benefits can be assessed (Avan et al., 2015). Commonly these benefits are attributed to the large bilateral effect of head shadow (attending to the input with the more favorable SNR), the smaller binaural effect of squelch (centrally combining differences across inputs) and the smallest binaural effect of summation or redundancy (combining two inputs with an identical SNR; Dillon, 2012). While the exact physiological mechanisms mediating these binaural benefits remain unclear, their presence has been demonstrated even in asymmetric hearing situations like bimodal hearing (Avan et al., 2015).

Just as in other studies in this field (e.g., Dincer D'Alessandro, Sennaroğlu, Yücel, Belgin, & Mancini, 2015), a substantial amount of variability between bimodal participants was observed. However spatial bimodal effects were consistently found in this study, in contrast to the sometimes inconsistent and nonsignificant outcomes reported in earlier studies (Gifford et al., 2014; Schafer et al., 2011). In this study, all testable participants experienced some SNR improvement with bimodal aiding in multiple spatial conditions.

The poorest performance in a monaural condition was observed for speech coming from the frontal direction while noise was presented from the CI-side (S0Nci). This is not surprising given the fact that the CI was the primary speech input for most participants. Accordingly the largest bimodal effect of 5.9 dB was obtained when the HA was added in this condition. This effect reflects not only the ability to listen with both ears but also head-shadow effects on the effective speech-to-noise ratio at each ear (Dillon, 2012). This head shadow effect has been reported to be the most robust benefit of bimodal speech intelligibility in noise (Schafer et al., 2011). Previous studies using a comparable set-up and procedure in bimodal participants noted average improvements of between 3.7 and 6.3 dB (Iwaki et al., 2004; Mok, Grayden, Dowell, & Lawrence, 2006; Morera et al., 2012), which concurs with the effect found in this study.

Rather than attending to one ear or the other, the bimodal benefits in the other two spatial conditions represent listeners' ability to combine information across both ears. When speech and noise both came from the

front, a bimodal summation effect of 4.2 dB was found. When the HA input was added with an inferior SNR, a bimodal release from masking of 2.6 dB was found. In this spatial condition, the effect is often attributed to the binaural squelch phenomenon (Avan et al., 2015). Comparable bimodal studies refer to significant benefits of squelch and summation with an average size of 2.6 to 3.6 dB (Kokkinakis & Pak, 2014; Morera et al., 2012) and 1.1 to 7.6 dB, respectively (Ching, van Wanrooy, Hill, & Dillon, 2005; Iwaki et al., 2004; Kokkinakis & Pak, 2014; Mok et al., 2006; Morera et al., 2012; Vroegop, Dingemans, Homans, & Goedegebure, 2017). The current study demonstrated a similar squelch effect and a rather large summation effect. It has been shown before that test procedures, material, and inclusion criteria may influence results (Dorman et al., 2014; Schafer et al., 2011). With average aided thresholds of 40 dB HL or better up to 1000 Hz, the included participants in the current study demonstrate more potential to benefit from residual hearing capacities in the HA ear than those included in most other studies. Unlike other hearing-impaired individuals who use bilateral identical devices, bimodal listeners are predefined to have asymmetric hearing. This can lead to significant benefits when the low-frequency acoustic ingredients of the HA ear are complementary to the characteristics of electric hearing with a CI. This complementary component of redundancy, probably fulfilled by the monaural extraction of fundamental pitch information (Avan et al., 2015; Brown & Bacon, 2010; Qin & Oxenham, 2006), seems to play a major role in the benefits of bimodal aiding (Schafer et al., 2011). Complementarity could therefore be responsible for the large bimodal summation effect. On the other hand, it is possible that the comparatively small bimodal squelch effect simply reflects the associated degree of summation instead of reflecting the true binaural integration of interaural level and time differences. It is namely known that due to timing and loudness inconsistencies across CI and HA devices and the limited frequency overlap between listening modes, the bimodal use of interaural differences in itself is limited (Francart & McDermott, 2013).

Although spatial speech-in-noise testing with an adaptive SRT-procedure is a well-established method to demonstrate bimodal benefits, it demands a specific set-up and extensive test time. Furthermore some CI recipients are unable to perform when testing speech-in-noise (Kaandorp et al., 2015; Schafer et al., 2011). In the current study, 4 out of 15 participants with incomplete results in noise could not be included in the corresponding analysis. Not surprisingly, it was seen that those participants were the poorest performers on CI speech intelligibility in quiet, with word scores of less than 50% (Appendix A). Although the closed-set sentence material used in this study has proven its applicability

in CI recipients (Theelen-van den Hoek et al., 2014), it is not surprising that an SRT-outcome in noise cannot be determined for CI recipients with speech recognition performance below 50% correct in quiet. In three of the excluded participants meningitis was assessed to be the cause of hearing loss (Table 1). It has been shown that meningitis-associated cochlear ossification can result in less favorable CI outcomes when implanted at a later age (Blamey et al., 2012; Durisin et al., 2010; Kraaijenga et al., 2015; Waltzman, Niparko, Fisher, & Cohen, 1995). Three out of four participants who were excluded from the final spatial speech in noise data analysis were able to perform in the bimodal condition but failed to reach an outcome below 15 dB SNR when listening with their CI alone (Appendix A). Therefore the presence of bimodal benefit could be hypothesized even though the actual degree could not be determined. Excluding these cases, if anything, may have resulted in an underestimation of the bimodal benefit in noise. Other studies often deal with the issue of not testable participants in noise by not including them in the first place (e.g., Buechner et al., 2014; Cullington & Zeng, 2011; Nelson & Jin, 2004). This, however, introduces a selection bias with the population of bimodal recipients not being fully represented. The current study aimed to gain more insight into the applicability of this outcome measure in a relevant bimodal sample and the characteristics of nontestable participants. Other measures of speech perception were also introduced here to target other dimensions of bimodal benefit applicable to the total range of bimodal recipients.

### *Listening Effort*

The proposed extended measures of bimodal speech perception could be obtained for all included participants. Provided that the relative SNR-levels were fixed to a maximum for those who were unable to perform speech intelligibility testing in noise, an overall significant release of listening effort up to 1.4 points could be demonstrated at higher individualized SNRs.

The intention of setting levels relative to the individual SRT was to enable the perceptual extension of listening effort per se, instead of an iteration of measuring subjective intelligibility (Preminger & Van Tasell, 1995a, 1995b). It has been reported, that reduction in perceived listening ease can be influenced by the listener's awareness of decreasing in speech understanding (Feuerstein, 1992). In the current study, which assessed effort in addition to intelligibility, exploratory correlation analysis suggested the benefit of listening effort to be a dimension in itself, since no clear relations with any of the other bimodal benefits were found (Table 3). It should however be noted that even though a correction was applied for the individual level of intelligibility at

SRT for the corresponding listening condition, both listening conditions (CIHA and CI) do not necessarily have to follow the same course of intelligibility across levels below and above SRT. Further research is then warranted to shed more light on the differences in psychometric functions between bimodal listening conditions.

The results demonstrated a reduced rated effort at more favorable SNRs. At higher individualized SNRs, reasonably good levels of speech intelligibility of 50% up to 100% are expected, while noise still challenges the listening situation (Rönnberg et al., 2014). It has been reported that listening effort can be reduced even if speech intelligibility is at its maximum level (Klink et al., 2012), since limited abilities like degraded spectral resolution can result in increased effort even when intelligibility is at 100% (Winn & Edwards, 2013). Listening effort therefore has been demonstrated to be a sensitive measure to assess the transmission of speech, especially at high levels of performance in noise (Morimoto, Sato, & Kobayashi, 2004). It has, for example, been suggested that the effect of noise modulations may only be apparent at better SNRs (Rönnberg, Rudner, Lunner, & Zekveld, 2010). Research into the cognitive capacities related to speech perception indicates that at poor SNRs, working memory capacity plays a major role, while at more favorable SNRs, the importance of the executive function of updating gains importance (Ellis & Rönnberg, 2014; Rönnberg et al., 2014; Rudner, Rönnberg, & Lunner, 2011). Given the within-subjects design of the current study, basic cognitive capacities of tested participants did not differ between listening conditions. However it can be imagined that when more complementary information becomes available by adding the acoustic to the electric input, the executive functions of processing and updating this information, in particular, experience a lower workload while the amount of extracted information to be stored in memory stays the same given the same stabilized level of intelligibility. Just as in other studies (Rudner et al., 2012; Schulte et al., 2008), the amount of effort decreased at higher SNRs. But while effort stagnated at higher levels when listening with a CI alone, a further decline was observed for the bimodal listening situation. It should however be noted that even with bimodal aiding, the rated effort was far from zero since it dropped only to 5 on a 12-point scale.

A simple scaling method at individualized SRT levels demonstrated here to be a simple and fast way to address bimodal listening ease. Testing all levels with the used scaling procedure required about 15 minutes time, leaving a single level testable within only a few minutes.

## Sound Quality

Even though the feedback provided by bimodal users indicates an improvement in sound quality experience, this study was the first to specifically quantify bimodal sound quality for multiple attributes. With this intention, a questionnaire based on known sound quality descriptors (Boretzki, 1999) was proposed and well received by bimodal users. Adding a contralateral HA in addition to a CI resulted not only in a less tinny sound (3.0/10), an effect found earlier (Christal, 2012), but also a more voluminous (2.3/10) and less unpleasant (1.4/10) sound quality experience. These outcomes closely reflect the experiences heard from clinical practice within the field of bimodal hearing (e.g., Potts, Skinner, Litovsky, Strube, & Kuk, 2009). They are also in line with a study, demonstrating that in normal-hearing listeners, binaural input delivers primarily more fullness and a better overall impression when compared with monaural hearing (Balfour & Hawkins, 1992). As shown in Table 2, and is known from the amount of residual hearing in the HA-ear (Figure 1), these descriptors relate to a reduced dominance of components in high-frequency regions and added components in low-frequency regions. Furthermore, the exploratory correlation analysis suggests that voluminous benefit is associated with benefit in the condition S0N0 (Table 3), which is not surprising in the light of the known phenomenon of loudness summation (Moore & Glasberg, 2007).

## Residual Hearing

With inclusion criteria broadening over the years, more candidates with relatively more residual hearing have become CI recipients (Gifford et al., 2010; Hughes et al., 2014). It has been shown that low-frequency residual hearing plays an important role in bimodal hearing (Büchner et al., 2009; Illg, Bojanowicz, Lesinski-Schiedat, Lenarz, & Büchner, 2014; Kong, Stickney, & Zeng, 2005; Mok, Galvin, Dowell, & McKay, 2010). Many previous studies, however, did not find a significant correlation between measures of bimodal benefit and residual hearing thresholds in the HA-ear (Beijen, Mylanus, Leeuw, & Snik, 2008; Ching, Incerti, Hill, & van Wanrooy, 2006; Dincer D'Alessandro et al., 2015; Litovsky, Johnstone, & Godar, 2006; Mok et al., 2006; Veugen, Chalupper, Snik, van Opstal, & Mens, 2015, 2016; Yoon, Shin, & Fu, 2012). Others on the other hand have suggested that more residual hearing leads to more bimodal benefit (Dorman et al., 2015; Firszt, 2008; Zhang et al., 2013).

Although this group of participants has fairly favorable residual hearing, a clear correlation could not be discerned between hearing thresholds and the largest

effects of speech intelligibility or listening effort in noise. It should be kept in mind, however, that due to small sample size, we are confronted with limited statistical power. At the same time, other studies have not been able to fully explain the specific origins of the large intersubject variations in bimodal benefits. Explanations have been proposed such as spectral resolution of the HA ear (Zhang et al., 2013) or differences in the characteristics of the two ears (Yoon, Shin, Gho, & Fu, 2014).

## Limitations and Relevance

Prior studies have evaluated bimodal speech intelligibility (Gifford & Dorman, 2012; Gifford et al., 2014; Kokkinakis & Pak, 2014; Morera et al., 2012; Schafer et al., 2011). The novel contribution of the current study lies in the fact that it aimed at pointing toward the content and applicability limitations of intelligibility outcome measures. This was demonstrated by evaluating a bimodal test battery within a recent clinical sample introducing other outcome measures such as listening effort and sound quality. Indeed the results could illustrate that listening effort and sound quality were outcome measures of bimodal benefit on top of intelligibility, which are clinically testable across the whole range of bimodal participants, in contrast to the more complex research originated measure of spatial intelligibility in noise. Like other CI studies into the benefits of bimodal aiding (Schafer et al., 2011), the present study had a limited sample size. The relationship between the tested dimensions of bimodal benefit and residual hearing (Table 3) could therefore only be examined with simple correlation analysis, given the number of assessed variables and limited power. This precludes making strong conclusions and generalizing the obtained results to the total population of bimodal recipients. The current sample can be considered representative of bimodal participants being currently fitted, having CI speech intelligibility scores in quiet ranging from 0% up to 96% (Dorman et al., 2008, 2015; Zhang et al., 2013) and aidable hearing in the HA ear up to 1000 Hz on average (Hughes et al., 2014; Yoon et al., 2012). So even though any conclusions drawn must be considered with caution, the results make a relevant contribution to the current field of bimodal aiding, while providing suggestions for future research. Furthermore, the directions resulting from the presented set of outcome measures may also extend toward related research areas and patient populations such as combining input across equally aided ears (bilateral HAs or bilateral CIs) or combining acoustic and electric input within the same ear (electro-acoustic stimulation). Nevertheless the test battery should be

further evaluated in a larger set of patients and settings to gain more insight into the relationship between benefits, the mechanisms underlying these benefits, and ways to optimize them.

## Conclusion

This study was conducted to extend the common measures of speech perception to include other dimensions relevant to the current population of bimodally aided CI users. Measures of subjective listening effort and sound quality were applied in clinical practice, in addition to the more complex testing of spatial speech in noise. Significant benefits of combining the CI with a conventional HA in opposite ears were observed across tested speech perceptual dimensions. As in other studies, all tested bimodal improvements of speech intelligibility were obtained in different spatial settings of speech and noise. Moreover a reduction of listening effort was present at the highest SNRs tested. Furthermore it was established that bimodal hearing reflected a more voluminous, less tinny, and more pleasant sound experience. Listening effort and sound quality suggested complementary outcomes. Therefore it is advisable to take various dimensions of speech perception into account when assessing bimodal benefit in current clinical CI populations.

## Trial Information

This study was registered as part of a larger clinical trial in the Dutch National Trial Register (NTR3932).

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## Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: J. C. holds a scientific post in the Advanced Bionics European Research Center. The study was designed in cooperation between MUMC+ and Advanced Bionics. Data collection, analysis, and the decision to publish

were all solely accounted for by MUMC+. The work presented in this manuscript is the intellectual property of MUMC+.

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